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FAILURE RADIUS: THEORY AND PREDICTION

BY D. J. PASTINE
D. J. EDWARDS

RESEARCH AND TECHNOLOGY DEPARTMENT

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NAVAL SURFACE WEAPONS CENTER

Dahlgren, Virginia 22448 • Silver Spring, Maryland 20910

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A theory is presented which relates the Chapman-Jouquet pressure of a detonating explosive to its charge radius and also predicts the failure radius. This theory results in a one parameter equation. This equation fits the experimental data for cast TNT reasonably well when the parameter is obtained using one datum point.

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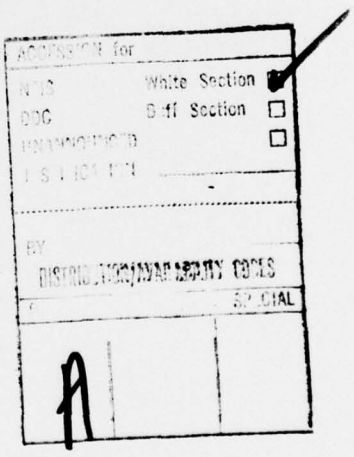
FAILURE RADIUS: THEORY AND PREDICTION

This work was carried out under Task SF33354316. The present results and conclusions on failure diameter should be of interest in the area of explosive applications.

J. W. Enig

J. W. ENIG
By direction



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INTRODUCTION

The failure diameter of an explosive composition is an important characteristic which, to some extent, determines the composition's usefulness from an application's viewpoint. The failure diameter is that dimension through which a steady detonation cannot be propagated. One class of explosives which has evoked a great deal of interest in recent years has been labeled "non-ideal" explosives. This class of explosives is not thought to react completely within the steady state detonation wave. For this discussion non-ideal explosives are compositions containing an ideal explosive (RDX, HMX), aluminum, and an oxidizer (ammonium nitrate, ammonium perchlorate). The failure diameters of non-ideal explosives are usually much greater than those of ideal explosives. The usual method of determining failure diameter is to fire a series of cylindrical test charges of different diameter. This is an expensive and time consuming process, especially if one is developing a new composition. The ultimate goal of this work is to predict the failure diameter of an explosive composition on the basis of the physical properties of its constituents.

To be able to predict failure diameter in this manner, the physical properties related to failure diameter must be determined. Two properties which seem clearly related to detonation failure are the speed of sound, c, in the steady detonation wave and the reaction zone length, ℓ. Rarefaction waves entering from the cylindrical edges of the steady detonation front can certainly quench or slow reaction if they penetrate deeply enough into the steady wave. They can also cause curvature of the detonation front. The depth of penetration will depend on the sound speed and the time available for propagation into the steady wave regime. The latter time will in turn depend on reaction zone length. It is rather interesting that in adding aluminum to explosives both of these quantities may be expected to increase. The sound speed which ordinarily decreases when small quantities of aluminum are added to explosives will probably increase (due to the same aluminum presence) in the dense regions behind a detonation front. In addition, the slower energy release rate associated with reacting aluminum should extend the length of the steady detonation wave (reaction zone). Such explosives should, therefore, be expected to have larger failure diameters than their non-aluminized counterparts.

DIAMETER EFFECT

The phenomenon known as diameter effect in condensed explosives is no more than the experimental fact that the detonation velocity, D, of a cylindrical charge decreases as the diameter of the charge decreases. This relationship between detonation velocity and diameter

has been studied theoretically by Jones,[1] Eyring, Powell, Duffey, and Parlin,[2] Wood and Kirkwood,[3] Sichel,[4] and Dubnov,[5] to mention a few. (Actually, Wood and Kirkwood were concerned with radius of curvature of the detonation wave and not the diameter). The relationships which have been derived by these researchers can be put into the form,

$$\frac{D}{D_o} = 1 - \frac{A\ell}{R} \tag{1}$$

where D_o is the detonation velocity at infinite diameter, ℓ is the reaction zone length, R is the radius of the charge, and A is a constant (which is dependent on the model used to derive it). This equation could be used to predict failure diameter (1) if ℓ was a constant for varying R or (2) if a relationship between ℓ and R could be obtained. If condition (1) were true, the problem would be trivial. However, ℓ is not constant as will be shown below. Condition (2) is a possibility because ℓ does vary with R.

MODIFICATION OF D VERSUS 1/R EQUATION

The reaction zone length of an explosive is related to the sound speed in the reaction zone and the reaction time, τ, by

$$\ell = \int_o^\tau c(t)\, dt. \tag{2}$$

At the present time c(t) is an unknown function which depends on the reaction kinetics of the explosive. In a steady detonation, c(t) is thought to be a monotonically decreasing function of time, thus Equation (2) can always be rewritten in the form

$$\ell = \bar{c}\ \tau \tag{3}$$

where $\bar{c} = \frac{1}{\tau} \int_o^\tau c(t)\, dt$, and should satisfy $c_f \geq \bar{c} \geq c_{CJ}$, c_f is the sound speed at the detonation front, and c_{CJ} is the sound speed at the end of the reaction zone. Substituting Eq. (3) into Eq. (1) yields

$$\frac{D}{D_o} = 1 - \frac{A\bar{c}\tau}{R}. \tag{4}$$

1. H. Jones, Proc. Roy. Soc. (London), A189, 415 (1947).
2. Eyring, Powell, Duffey, and Parlin, Chem. Revs., 45, 69, (1949).
3. Wood and Kirkwood, Jour. Chem. Phys., 22, 1920-24 (1954).
4. M. Sichel, AIAA Jour., 4, 264-72 (1966).
5. L. V. Dubnov, Russ. Jour. Phys. Chem., 34 (10), 1124-25 (1960).

To proceed further requires a set of data on an explosive which gives D and τ as a function of R for various R's including the failure radius, R_f. Dremin, Saviov, Trofimov, and Shvedov[6] have published such data for cast TNT at densities of 1.62 and 1.60 g/cc. Table 1 lists this data (Table 2 of reference 6). The difference in density (and failure radius) is due to different methods of casting. ".....The trotyl [TNT] castings of the first type were obtained by cooling the melt with the continuous stirring. They had a homogeneous fine-crystalline structure throughout the entire cross section of the charge. The density of such castings, determined by analytic suspension in water, amounted to 1.62 g/cm^3. Castings of the second type were manufactured similarly, but the melt was cooled without stirring. As a result castings were obtained with large crystals, extending from the periphery to the center, and their density was 1.6 g/cm^3 on the average...."[6] P_{CJ} and u_{CJ} in Table 1 are the pressure and particle velocity at the end of the reaction zone. The detonation parameters in Table 1 were obtained by Dremin as follows. D was determined by streak camera measurements. u_{CJ} and τ were obtained from the break point in the u(t) profile obtained from electromagnetic velocity gages located on the axis of the charge. P_{CJ} was obtained from $P_{CJ} = \rho_o u_{CJ} D$; ℓ was obtained from $\ell = \tau (D - 1.25 u_{CJ})$.* Since there is only a 1% difference in density, one value of D_o (7.04 mm/μsec) will be used for these two densities.

It is obvious from Table 1 that ℓ is not a constant for varying R. The next question is: Is A of Equation (1) a constant? Solving Equation (1) for A one obtains

$$A = \left(1 - \frac{D}{D_o}\right) \frac{R}{\ell} . \qquad (5)$$

For 1.62 g/cc TNT, A varies from 0.071 at R = 30 mm to 0.461 at R = 8 mm.

Up to this point, only the variation of $\frac{D}{D_o}$ with ℓ and R has been considered. The data of Table 1 can also be used to look at the variation of P_{CJ} with ℓ and R. An equation similar to Equation (1) or Equation (4) involving P_{CJ} can be obtained using the approach of Dubnov.[5] The Infinite Diameter C-J pressure, P_{CJo}, of an explosive is defined[5] by

$$P_{CJo} = G(\rho_o)\, Q\, (\gamma - 1) \qquad (6)$$

*Russian researches have noted that the extrapolated particle velocity at the detonation front using the EMV gage is usually 1.5-1.6 u_{CJ}. The particle velocity-time profiles obtained are essentially linear. Thus they use the average value of the particle velocity in the reaction zone (1.25 u_{CJ}) to compute ℓ. This approach, however, ignores any possibility of an induction zone behind the detonation front.

5. L. V. Dubnov, Russ. Jour. Phys. Chem., 34, (10), 1124-25 (1960).
6. Dremin, Saviov, Trofimov, and Shvedov, Detonation Waves in Condensed Media, (English Translation).

Table 1

Detonation Parameters of Cast TNT versus Charge Radius*

R mm	D mm/μsec	u_{CJ} mm/μsec	P_{CJ} Kbar	τ μsec	ℓ mm
		ρ_o = 1.62 g/cc			
30	6.98	1.62	183.2	0.26	1.27
20	6.95	1.60	180.1	0.28	1.36
14	6.89	1.52	169.5	0.30	1.47
12.5	6.84	1.36	150.7	0.31	1.57
11	6.75	1.31	143.2	0.30	1.51
10	6.64	1.24	133.3	0.34	1.71
9	6.52	1.20	126.7	0.33	1.64
8**	6.36	1.10	113.3	0.36	1.77
		ρ_o = 1.60 g/cc			
30	6.85	1.60	175.5	0.30	1.43
20	6.74	1.49	159.6	0.315	1.51
17.5	6.70	1.43	152.3	0.31	1.50
15	6.37	1.39	140.8	0.34	1.55
13.75**	6.20	1.20	119.0	0.35	1.67

* From Table 2 of Reference 6
** Failure radius of the charge

where $G(\rho_o)$ is a function of the initial density of the explosive, Q is the total heat of the explosion, and γ is the index of polytropy of the detonation products.* Taking into account the losses due to the lateral spreading of the products away from the reaction zone, Equation (6) is rewritten as

$$P_{CJ} = G(\rho_o)\ Q\ (\gamma - 1)\eta \tag{7}$$

where P_{CJ} is the actual pressure and η is a factor characterising that part of Q that goes into the shock wave. Thus

$$\frac{P_{CJ}}{P_{CJo}} = \eta . \tag{8}$$

Taking the square root of Equation (8) one obtains

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2} = \sqrt{\eta} . \tag{9}$$

Equation (9) is similar to Equation (4) of reference (5). From reference (5), η is the ratio of unaffected volume to the total volume in the reaction zone, and

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2} \approx 1 - \frac{\ell}{2R} , \tag{10}$$

Since the coefficient is dependent on the approach, Equation (10) will be generalized to

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2} = 1 - \frac{A'\ell}{R} . \tag{11}$$

P_{CJo} (in k bar) is obtained from

$$P_{CJo} = 10\ \rho_o\ u_{CJo}\ D_o \tag{12}$$

where D_o = 7.04 mm/μsec for both densities.** u_{CJo} for the TNT in Table 1 is obtained by using γ = 3 in

$$u_{CJo} = \frac{D_o}{\gamma + 1} , \tag{13}$$

*The assumption is made here that detonation products are describable by an isentropic equation of the form Pv^{γ} = constant.

**This value was obtained by fitting D vs 1/R.

5. L. V. Dubnov, Russ. Jour. Phys. Chem., 34 (10), 1124-25 (1960).

with the result that u_{CJo} = 1.76 mm/μsec. Thus P_{CJo} = 200.7 Kbar for ρ_o = 1.62 and P_{CJo} = 198.2 Kbar for ρ_o = 1.60 g/cc. Table 2 lists A, D/D_o, A', and $(P_{CJ}/P_{CJo})^{1/2}$. For 1.62 g/cc TNT, A varies by a factor of 2.39 while A' varies by a factor of 1.46; for 1.60 g/cc, A varies by 1.73 while A' varies by 1.50.

Changing from D to P_{CJ} does not seem to matter as far as the terms A and A' are concerned. However, close examination of the data in Table 2 shows that P_{CJ} is more sensitive to R than D is. For ρ_o = 1.62 g/cc TNT P_{CJ} at failure diameter is reduced to 56% of its infinite diameter value while D is reduced to only 90%; for ρ_o = 1.60 g/cc TNT P_{CJ} is reduced to 60% while D is reduced to 88%.

In Equation (4), $\bar{c}$ can be related to P_{CJ} as follows. The quantity $\bar{c}$ lies between c_f and c_{CJ} and, it is reasonable to assume that $\bar{c}$ can be written as a linear function of c_f and c_{CJ}.

The quantity c_{CJ} is given by

$$c_{CJ} = D - u_{CJ} = D - \frac{D}{\gamma+1} . \tag{14}$$

Since it follows from Equations (12) and (13) that D is proportional to $\sqrt{P_{CJ}}$, then the result $c_{CJ} \propto \sqrt{P_{CJ}}$ also follows from Equation (14). The quantity c_f can be closely approximated by terms linear in D and u_f, i.e. $c_f = D + bu_f$ where b is a constant approximately equal to two. Since $D \propto \sqrt{P_{CJ}}$, and, since it has been observed that $u_f \approx 1.5\ u_{CJ}$, it follows the c_f is also approximately proportional to $\sqrt{P_{CJ}}$. Accordingly, $\bar{c}$ is written in the form

$$\bar{c} = A'' \sqrt{P_{CJ}/P_{CJo}} \tag{15}$$

where Equation (15) has been normalized to P_{CJo}.

The next question is: Can τ be related to P_{CJ}. Walker and Wasley[7] have proposed a critical energy fluence, E_c, for shock initiation of explosives

$$E_c = \frac{P^2 t}{\rho_o U_s} \tag{16}$$

where P is the pressure, t is the duration of constant pressure shock pulse, and U_s is the shock velocity in the explosive at pressure P. Does an equation similar to Equation (12) hold for the steady detonation regime? Three possible equations were investigated:

$$E = \frac{P_{CJ}^2 \tau}{\rho_o D} \tag{17}$$

$$E = \frac{P_f^2 \tau}{\rho_o D} \tag{18}$$

7. Walker and Wasley, Comb and Flame, 22, 53-58 (1974).

Table 2

Values of A and A' for Cast TNT

R mm	D/Do	A mm	$(P_{CJ}/P_{CJo})^{1/2}$	A' mm
		ρ_o = 1.62 g/cc		
30	0.991	0.213	0.955	1.063
20	0.987	0.191	0.947	0.779
14	0.979	0.200	0.919	0.771
12.5	0.972	0.223	0.866	1.067
11	0.959	0.299	0.845	1.129
10	0.943	0.333	0.815	1.082
9	0.926	0.406	0.795	1.125
8	0.903	0.438	0.751	1.125
		ρ_o = 1.60 g/cc		
30	0.973	0.566	0.941	1.238
20	0.957	0.569	0.897	1.364
17.5	0.951	0.571	0.877	1.435
15	0.905	0.919	0.842	1.529
13.75	0.881	0.980	0.775	1.853

where P_f is the pressure at the detonation front. P_f is obtained by using $P_f = 10\rho_o u_f D$. u_f is the particle velocity at the detonation front and is obtained from the unreacted Hugoniot. For TNT at ρ_o = 1.614 g/cc, the unreacted Hugoniot[8] is U = 2.39 + 2.05 u where U is the shock velocity in mm/μsec. The third equation is

$$E = \frac{\int_o^\tau P^2 dt}{\rho_o D} . \tag{19}$$

The integral in Equation (19) is evaluated by assuming that P varies linearly with t from P_f to P_{CJ}. This assumption was used because the measured u(t) profiles were essentially linear.[6] E is the energy flux along the axis of the charge.

The results of Equation (17), (18), and (19) are given in Table 3. Except for data close to the failure diameter the individual results for Equations (18) and (19) are within ~10% of the average for each equation. This is exceptional considering the possible error in the measurements. The results for Equation (17) are not quite as good. The individual results are within ~30% of the average. This is not bad considering that there is more error in measured values of P_{CJ} than D (and hence P_f). Again, if an equation of state existed for the reaction products and intermediate products, then P_{CJ} could be calculated from and perhaps be more accurate than the measured values. Thus, the indications are that τ can reasonably be related to P_{CJ} as follows:

$$\tau = A'''/(P_{CJ}/P_{CJo})^2 \tag{20}$$

where Equation (20) has been normalized to P_{CJo}.

An equation involving only P_{CJ} and R can now be obtained. Substituting Equation (3) into Equation (11) results in

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2} = 1 - \frac{A'\bar{c}\,\tau}{R} . \tag{21}$$

Substituting Equation (15) for $\bar{c}$ and Equation (20) for τ there results

6. Dremin, Saviov, Trofimov, and Shvedov, Detonation Waves in Condensed Media, (English Translation).
8. Coleburn and Liddiard, J. Chem. Phys., 44, 1929 (1966).

Table 3

P^2 versus τ for Cast TNT

R mm	Equation (17)	Equation (18)	Equation (19)
	$Kbar^2$-cc-μsec^2/mm-gm		
	ρ_o = 1.62 g/cc		
30	7.7×10^2	1.43×10^3	1.065×10^3
20	8.0	1.55	1.123
14	7.7	1.61	1.130
12.5	6.4	1.61	1.058
11	5.6	1.49	0.959
10	5.6	1.57	0.997
9	5.0	1.42	0.895
8	4.5	1.40	0.854
	ρ_o = 1.60 g/cc		
30	8.4×10^2	1.55×10^3	1.139×10^3
20	7.4	1.51	1.082
17.5	6.7	1.45	1.015
15	6.6	1.31	0.937
13.75	5.0	1.19	0.800

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2} = 1 - \frac{A'A"A'''}{R\left(\frac{P_{CJ}}{P_{CJo}}\right)^{3/2}} \tag{22}$$

or

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2} = 1 - \frac{\beta}{R(P_{CJ}/P_{CJo})^{3/2}} \tag{23}$$

where $\beta = A'A"A'''$.

FAILURE DIAMETER PREDICTION

The main question is: Does Equation (23) predict a point of failure? And if so, how does it compare with experiment? The first question is the same as asking: Does Equation (23) have an infinite derivative in the $(P_{CJ}/PCJo)^{1/2}$ versus 1/R plane? To determine this the derivative $d(P_{CJ}/P_{CJo})^{1/2}/d(1/R)$ must be obtained. For simplicity let $(P_{CJ}/P_{CJo})^{1/2} = x$ and $1/R = q$. Then Equation (23) becomes

$$x = 1 - \frac{\beta q}{x^3} \tag{24}$$

or

$$x^4 - x^3 = -\beta q . \tag{25}$$

Differentiating Equation (25) yields

$$4x^3dx - 3x^2dx = -\beta dq \tag{26}$$

or

$$\frac{dx}{dq} = \frac{-\beta}{4x^3-3x^2} \tag{27}$$

$$\frac{dx}{dq} = \frac{-\beta/4}{x^2(x-3/4)} . \tag{28}$$

At failure

$$\frac{dx}{dq} = -\infty \rightarrow x_f = 0.75 .$$

Thus Equation (23) has a vertical node in the $P^{1/2}$ versus 1/R plane when

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2}_{failure} = 0.75 \qquad (29)$$

or

$$\left(\frac{P_{CJ}}{P_{CJo}}\right)_{failure} = 0.56 . \qquad (30)$$

Thus Equation (23) predicts that there is value of R, designated R_f, for which no solutions exist when $R<R_f$. Therefore, R_f is the predicted failure radius of an explosive.

The answer to the question on comparison with experimental results can be obtained for cast TNT, at least. First of all, Equation (23) predicts that the radius will be reached when $P_{CJ}/P_{CJo} = 0.56$. As was mentioned earlier, failure occurs at $P_{CJ}/P_{CJo} =$ 0.56 and 0.60 for 1.62 g/cc and 1.60 g/cc cast TNT, respectively. Thus as far as the ratio of P_{CJ}/P_{CJo} is concerned, Equation (23) works well for cast TNT.

A calculated curve in the $(P_{CJ}/P_{CJo})^{1/2}$ versus 1/R plane can be obtained as follows. A value for β is obtained by using one $(P_{CJ}/P_{CJo})^{1/2}$, R datum point and substituting it into Equation (23). Using this β, the curve is generated by varying either $(P_{CJ}/P_{CJo})^{1/2}$ or R and solving for the other parameter. Figure 1 presents the calculated and experimental results for 1.62 g/cc TNT. The solid circles are from Table 2 and were calculated using Dremin's data.[6] The solid curve was calculated using Equation (23) and the datum point at R = 30 mm with β = 1.176 mm. The predicted R_f associated with this curve is 11.5 mm while the measured failure radius is 8 mm. The predicted R_f is 44% too large. Note, however, that the solid curve in Figure 1 passes through only the datum point used to generate it. All the other data points lie to the right of the solid curve. The dashed curve in Figure 1 was generated using the datum point at R = 20 mm (β = 0.900 mm). This curve appears to fit the data better and R_f is 8.5 mm or 6.3% larger than the measured value. The difference in the calculated curves is due to the error in the CJ pressure, either the measured P_{CJ}, or the calculated P_{CJo}, or both. Dremin[6] unfortunately does not give a value for the error in pressure. But, for example, an error of 5% (which would be excellent) easily reconciles the difference in the calculated curves.

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6. Dremin, Saviov, Trofimov, and Shvedov, Detonation Waves in Condensed Media, (English Translation).

Figure 2 presents the calculated and experimental results for 1.60 g/cc TNT, the solid circles are from Table 2. The solid curve was generated using Equation (23) and the datum point at R = 30 mm with β = 1.475 mm. The predicted R_f is 13.98 mm compared to the measured value of 13.75 or 1.7% too large. This curve fits the data so well that no other points were used for comparison.

In Table 2, the variation of A' with $(P_{CJ}/P_{CJo})^{1/2}$ was presented. A' varied by a factor of 1.46 for 1.62 g/cc and 1.73 for 1.60 g/cc TNT. In Table 4, the calculated values of β for each datum points are presented. For 1.62 g/cc TNT, β varies by a factor of 1.39; for 1.60 g/cc TNT, β varies by 1.08. For 1.62 g/cc TNT, the variation of β and A' are essentially the same. For 1.60 g/cc TNT, β is essentially constant while A' varies by 73%. Note also that the actual values of β and A' are very close. However, until the physical meaning of β is explained, no physical significance is attached to this.

PHYSICAL INTERPRETATION OF THE RESULTS

A theory is presented which relates the Chapman-Jouquet pressure of a detonating explosive to its charge radius and also predicts the failure radius. The question remains: What is the physical meaning of this theory? First, this theory was developed by comparing the ratio of the total energy available to the actual energy which is unaffected by lateral rarefaction. This resulted in Equation (11). The same equation results if the ratio of the energy flux through the unaffected C-J surface to the energy flux through the detonation front is used as a starting points. The important point about either approach are: (1) the unaffected energy is the governing parameter, and (2) the Chapman-Jouquet pressure is the measurable parameter most sensitive to changes in energy.

The second crucial step was the assumption that P^2t = constant holds in the reaction zone over the range of pressure considered. An alternate way of stating this is that the reaction along a streamline, which is not affected by lateral rarefaction, will proceed until all the energy is released. The time required for this reaction process is, in turn, directly dependent on the pressure.

SUMMARY AND FUTURE WORK

A one parameter equation (Equation (23)) has been developed which relates P_{CJo}, P_{CJ}, and R. This equation fits the experimental data for cast TNT reasonably well when the parameter β is obtained using one datum point and P_{CJo}. This equation also predicts the failure diameter of cast TNT reasonably well when the error in the pressure is taken into account. Unfortunately, no complete set of data containing P_{CJ}, R, and the failure diameter has been found for

Table 4

Values of β for Cast TNT

R mm	$\left(\frac{P_{CJ}}{P_{CJo}}\right)^{1/2}$	β mm
	ρ_o = 1.62 g/cc	
30	0.955	1.176
20	0.947	0.900
14	0.919	0.880
12.5	0.866	1.088
11	0.845	1.029
10	0.815	1.001
9	0.795	0.927
8	0.751	0.844
	Average	=0.981
	ρ_o = 1.60 g/cc	
30	0.941	1.475
20	0.897	1.487
17.5	0.887	1.380
15	0.842	1.415
13.75	0.775	1.440
	Average	= 1.439

a non-ideal explosive. Future experimental work will obtain such a set of data to check Equation (23) for a non-ideal explosive.

The derivation of Equation (23) relies heavily on the assumption that $\rho_{CJ}^2 \tau$ is a constant, Equation (20). The data for cast TNT indicates that this assumption is reasonable. Future theoretical work will investigate this relationship.

References

1) H. Jones, Proc. Roy. Soc. (London), A189, 415 (1947).

2) Eyring, Powell, Duffey, and Parlin, Chem. Revs., 45, 69 (1949).

3) Wood and Kirkwood, Jour. Chem. Phys., 22, 1920-24 (1954).

4) M. Sichel, AIAA Jour., 4, 264-72 (1966).

5) L. V. Dubnov, Russ. Jour. Phys. Chem., 34 (10), 1124-25 (1960).

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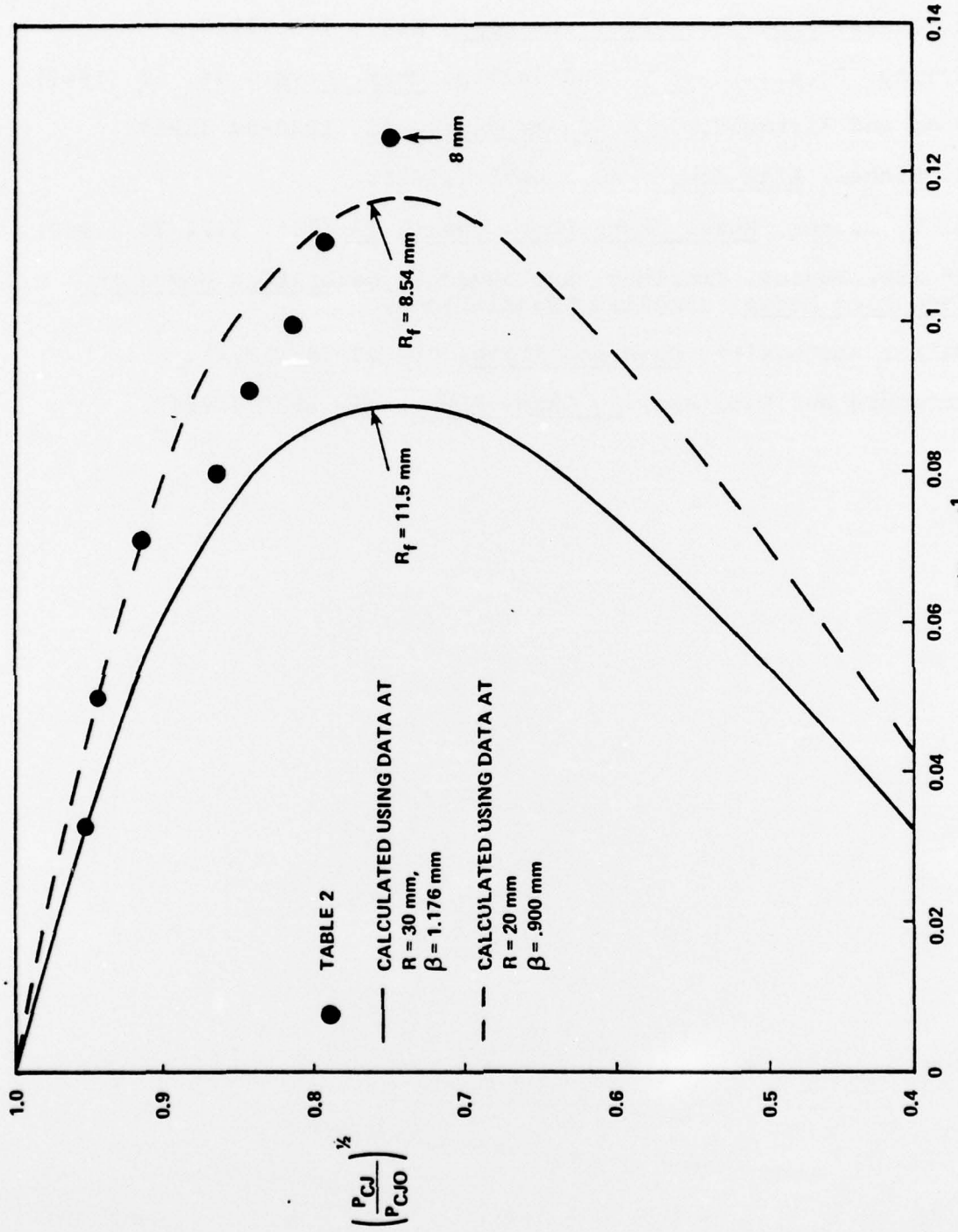

FIG. 1 COMPARISON OF PREDICTED AND EXPERIMENTAL $P^{\frac{1}{2}}$ VS. 1/R RESULTS FOR CAST TNT, ρ_o = 1.62 g/cc

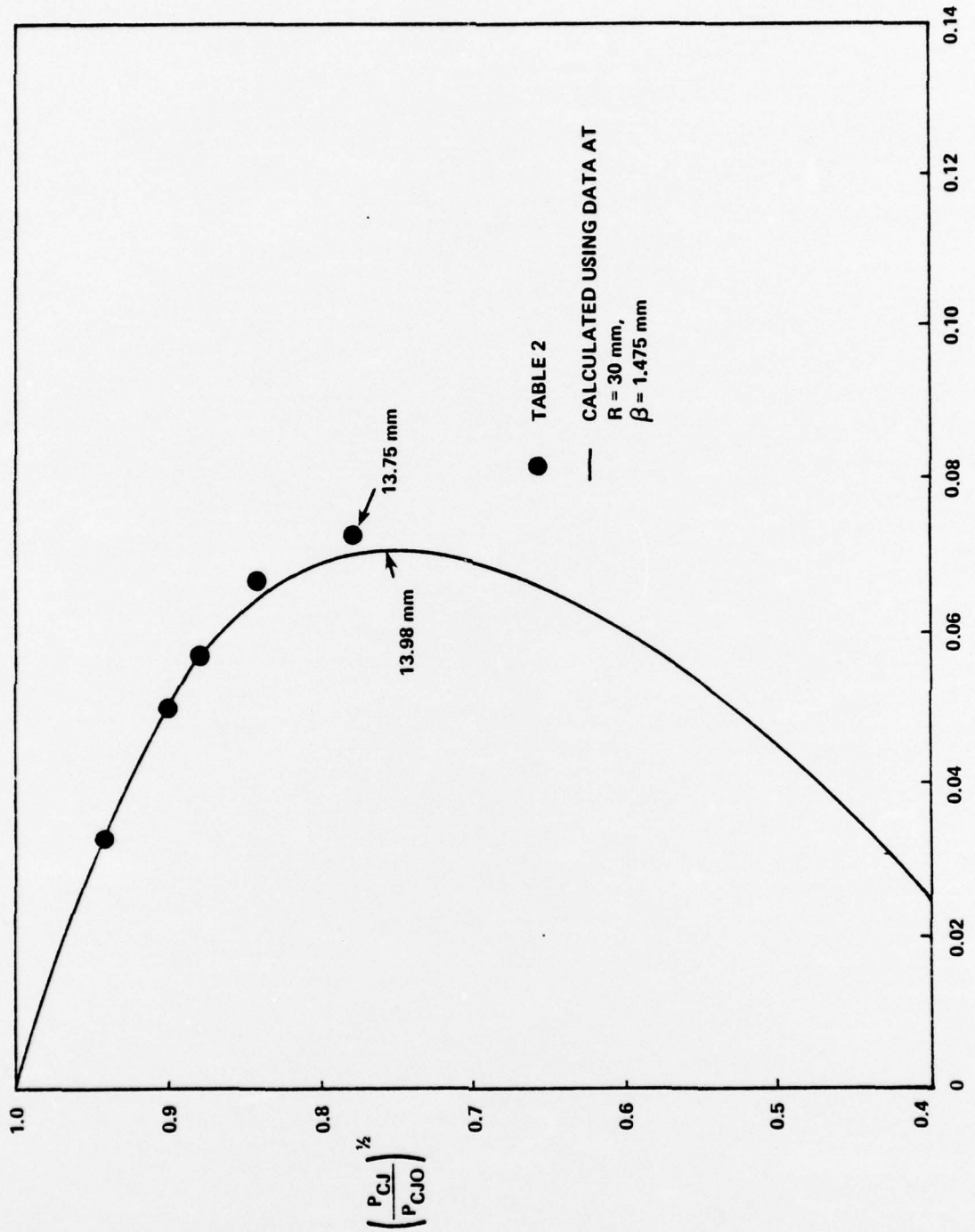

FIG. 2 COMPARISON OF PREDICTED AND EXPERIMENTAL $P^{\frac{1}{2}}$ VS. 1/R RESULTS FOR CAST TNT, ρ_o = 1.60 g/cc

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